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A MEASUREMENT OF THE CP VIOLATION PARAMETER η_{+-o}.

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ABSTRACT

We propose to measure the CP violation parameter, η_{+-0}, by measuring the time dependence of the interference between K_L and K_S decays into $\pi^+\pi^-\pi^0$. We would use the M2 beam and the "E8" spectrometer, modifying the beam to hit two targets, one to give the interference, and the other upstream to give pure K_L decays for normalization.

We would perform the experiment in two phases: first we would use the existing beam and apparatus to measure η_{+-0} to an accuracy of .003, then we would modify M2 to make a double beam, hit the two targets simultaneously, run for 1000 hours, and achieve an accuracy of $\frac{1}{2} \times 10^{-3}$ in the measurement of η_{+-0}.

I. Introduction

We propose to measure the CP violation parameter,

$$\eta_{+-0} = Amp(K_S \to \pi^+\pi^-\pi^0)/Amp(K_L \to \pi^+\pi^-\pi^0)$$

by studying the interference between K_S and K_L decays near their production target. The proper time, t, dependence of $\pi^+\pi^-\pi^0$ decays in an incoherent K^0, $\bar{K}^0$ beam is:

$$\frac{dN}{dt} = \frac{N_L B}{\tau_L} \left\{ e^{-t/\tau_L} + |\eta_{+-0}|^2 e^{-t/\tau_S} + 2D|\eta_{+-0}| \times \cos(\Delta m t + \varphi)\, e^{-t/2\tau_S} \right\} \qquad (1)$$

where N_L is the number of K_L's exiting from the target, B is the $K_L \to \pi^+\pi^-\pi^0$ branching ratio, $\tau_L (\tau_S)$ is the $K_L (K_S)$ lifetime, Δm is the K_L-K_S mass difference, φ is the phase of η_{+-0}, and D is the dilution factor (to be discussed later).

In the K^0, $\bar{K}^0$ system, the eigenstates of CP are $|K_1\rangle$ and $|K_2\rangle$, of eigenvalues +1 and -1 respectively, and the K_L and K_S can be written as:

$$|K_L\rangle = \{|K_2\rangle + \epsilon|K_1\rangle\}/\sqrt{1+|\epsilon|^2}$$
$$|K_S\rangle = \{|K_1\rangle - \epsilon|K_2\rangle\}/\sqrt{1+|\epsilon|^2}$$

where $\epsilon = 2.2 \times 10^{-3}$. A system of three pions must be in an I=0, 1,2, or 3 state, and these states have $CP=(-1)^I$, so $K_2 \to 3\pi$ (CP odd) will go to odd I states, and $K_1 \to 3\pi$ (CP even) will go to even I states, if CP is conserved in K_1 and K_2 decays. See the review article by Lee and Wu[1].

As Lee and Wu point out the two largest K_1 transitions are to I=1 and I=2 states. The $K_1 \to \pi^+\pi^-\pi^0$, I=2 transition does not violate CP, but due to the I=3/2 supression and the angular momentum barrier this transition is of order 2×10^{-3} compared to the $K_2 \to \pi^+\pi^-\pi^0$, I=1 transition. The contribution of the I=2 transition to this particular experiment is smaller yet, for the following reason. The K_S-K_L interference term in Eqn. 1 will have the form $\langle 3\pi, I=1 | T | K_2 \rangle \langle 3\pi, I=2 | T | K_1 \rangle$ due to this CP-allowed transition; because a 3π, I=1 state is symmetric under interchange of two pions, and the I=2 state is antisymmetric, the spatial parts of the I=1 (I=2) wave function must be symmetric (antisymmetric) to achieve overall symmetry. When we integrate this contribution to the K_S-K_L interference term over the whole Dalitz plot, the result will be zero. Figure 1 shows the acceptance over the Dalitz plot for this experiment. It is flat to a few percent, thus reducing the contribution of the I=2 final state to the 10^{-5} level compared to $K_2 \to 3\pi$, I=1.

So, as far as this experiment is concerned, the only 3π final states that count are those with I=1. There are two such states, with the $\pi^+\pi^-$ isospin equal to 0 or 2. If we define two amplitudes for decays to these final states,

$$\langle 3\pi; I_{3\pi}=1, I_{\pi^+\pi^-}=0 | T | K^0 \rangle = i A_1 e^{i\delta_1} ,$$

and $\langle 3\pi; I_{3\pi}=1, I_{\pi^+\pi^-}=2 | T | K^0 \rangle = i A_1' e^{i\delta_1'}$,

then the CP violation parameter is:

$$\eta_{+-0} = \epsilon + i \frac{\mathrm{Im}\, A_1}{\mathrm{Re}\, A_1} - \frac{i}{\sqrt{5}} e^{i(\delta_1'-\delta_1)} \frac{\mathrm{Im}\, A_1'}{\mathrm{Re}\, A_1} . \qquad (2)$$

The prediction of the superweak theory[2] is that A_1 and A_1' are both real, and $\eta_{+-0} = \epsilon$. Gauge theories with six quarks[3] predict that there should be a direct CP violation; i. e., Im A_1 and Im A_1' are not zero. They have arguments on the order of 1 mrad. If this is true then the direct CP violation could contribute to η_{+-0} as much as ϵ does!

However, PCAC and soft pion theorems allow you to relate A_1 (A_1') to the I=0 (I=2) 2π decay amplitude, A_0 (A_2) in Kleinknecht's notation[4]. In this case Arg A_1 = Arg A_0 = 0, and direct CP violation contributes only a small fraction of ϵ to η_{+-0}. PCAC and soft pion theorems are valid to the 10%-20% level for the CP conserving parts of the weak interaction (in K^+, K^0 decays, for example[5]), but no one knows if these theories hold for the CP violating parts of the weak interaction.

The theoretical prejudice is that $|\eta_{+-0}|$ is between about 1×10^{-3} and 4×10^{-3}, with considerable uncertainty in that range. If $|\eta_{+-0}| < 1 \times 10^{-3}$ were the case, perhaps a cancellation in Eqn. 2 or a separate ϵ_L and ϵ_S (with $\epsilon_S = 0$) could explain it. The latter case violates CPT however.[4] If $|\eta_{+-0}|$ were found to be $> 4 \times 10^{-3}$, that would be very interesting indeed. So an experiment with a sensitivity in the 10^{-3} range could make a <u>significant contribution</u> to the understanding of CP violation.

II. The Experiment

Past experiments shed little light on the subject. The one with best statistics, Metcalf et al.[6] collected only 384 events in the reaction $K^+p \rightarrow K^0 p \pi^+$ using a 2.4 GeV/c K^+ beam, giving a result $|\eta_{+-0}| = .21 \pm .24$. Their apparatus consisted of a wire chamber spectrometer looking at the bare target, and was limited by the integrated flux of K^+ mesons. To get better statistics, one must go to a magnetic channel, such as the one in the M2 beam, and give up the knowledge of whether the initial state was a K^0 or a $\bar{K}^0$. This introduces the dilution factor into Eqn. 1,

$$D = [1 - \bar{K}^0/K^0] / [1 + \bar{K}^0/K^0].$$

K^-/K^+ production ratios have been measured at high energies, and agree with fits done for K^0's (see ref. 7). The $\bar{K}^0/K^0$ ratio for this experiment is small, and is shown in figure 2.

So what is needed for this experiment is a magnetic channel, followed by a decay region, a Vee spectrometer, and a lead-glass wall. The perfect apparatus already exists in the M2 beam line. The biggest change necessary is to think of it as a "short neutral beam" rather than as a "hyperon beam".

Figure 3a shows the apparatus: following the sweeping magnet is a 24 meter long evacuated decay region, three drift chambers, the spectrometer magnet, three MWPC's, counters, and a lead-glass wall. Above and below the magnet aperture are additional gamma detectors, the A counters, consisting of scintillator anti-counters, 2 x_0 of Pb, and an MWPC, giving accurate position resolution for gamma-ray hits. In front of the lead-glass is a similar Pb/MWPC combination to improve the position resolution of the 4" x 4" lead-glass blocks.

The trigger would demand two charged particles in the spectrometer and two gamma-rays: both in the lead-glass, or one there and one in the A-counters.

Integrated over momentum, the acceptance is 95% for the charged particles, and 83% for the gamma-rays, 2/3 of the time both hitting the lead-glass. The acceptance over the Dalitz plot is quite flat, varying from the 77% average by about 3%.

III. Acceptance in z

The crucial question about the acceptance is its variation with z, the longitudinal vertex position. Although the z-dependence is quite flat, Monte Carlo simulations can predict it only to the 1% level, while the experiment requires an order of magnitude better knowledge. Therefore we propose to <u>measure</u> the acceptance by using a second target. If we target the proton beam 20 m upstream of the usual target position, the falling exponential will kill off the interference term for $K_{\pi 3}$'s in the decay region. We will then see only the $K_L \rightarrow \pi^+\pi^-\pi^0$ decays, which have the same distribution as the K_L term of the main target data: the difference in z distributions of the two data sets (main and upstream targeting) will be due to the interference term. The highest precision is achieved with equal numbers of events in the two data sets, collected simultaneously in a double beam geometry, switching the roles of the beams frequently.

Therefore we would modify the M2 beam line to make two beams in the same horizontal plane with a separation of about 1 cm from inner edge to inner edge. They would strike two targets and the produced K^0's would be defined by a double hole collimator in the hyperon magnet. Figure 3b illustrates this geometry. The roles of the beams would be interchanged frequently by moving the targets from beam to beam, allowing the different acceptances of the two beams to cancel out. This method eliminates possible systematic errors such as rate-dependent chamber efficiencies, and allows more $K_{\pi 3}$'s to be accumulated per Λ^0 or $K_{\pi 2}$ background trigger (because the Λ^0's and K_S's have more time to decay before the decay region if they come from the upstream target).

IV. Sensitivity and Resolution

To estimate the sensitivity of this experiment let us assume that $\eta_{+-0} = \epsilon$ in magnitude and in phase. A Monte Carlo calculation using the measured resolution of the detectors of the E8 spectrometer tells us the acceptance as a function of momentum and proper lifetime (or z of the decay). Then an analytic calculation of proper time distributions allows us to "generate" as many events as we care to, the number

$N_I(p,z)$ coming from the main or interference target, and the number $N_n(p,z)$ coming from the upstream or normalization target. If we form the ratio $N_I(p,z)/N_n(p,z)$ for the same z bin, the acceptance cancels and, summing over momentum, the proper time distribution of this ratio is shown in Fig. 4. The errors shown in the figure are statistical errors that come from the double beam flux calculation given below. Using these values and errors, generating poisson fluctuations thereby, and fitting to the known distribution yields standard deviations of about 10 degrees in the phase and about 25% in the magnitude of η_{+-0}.

The other two curves in Fig. 4 illustrate these same results, if $Im(A_1)/Re(A_1)$ in Eqn. 2 were $+\epsilon$ and $-\epsilon$ respectively; i. e. $\eta_{+-0} = \epsilon(1 \pm i)$, and show the experimental response to these cases.

One correction that must be made to achieve the accuracy quoted above has to do with the momentum spectra from the two targets: because of the different solid angles subtended by the two beams, at any momentum the fact that the average p_T is different makes the momentum spectra different. The variation over the range of interest is about 2%. To achieve an accuracy of $\frac{1}{2} \times 10^{-3}$, this correction must be known to 2% of itself. Past measurements by this collaboration[8] have determined this to about 4% accuracy, so a better determination must be made. By running a fraction of the time with the normalization target 15 m upstream of the interference target we double the solid angle of the normalization beam (while not compromising the quality of our normalization data more than 20%) and can measure a third point in average p_T to determine this correction.

The resolution of the spectrometer is illustrated in Figures 5-9. Sigma is 1% in kaon momentum, 7 Mev in K^0 mass, 0.1 m in vertex position, .03 τ_S in proper time, and .18 cm in target position (when we extrapolate along the kaon's trajectory, the target position is how close we come to the point where the K^0 was produced).

Errors in proper time determination can push events to the left or right in Fig. 4, but these errors occur on the few percent level and the net errors are smaller yet. Moreover they are the same for events from both targets, so that in the ratio N_I/N_n this error cancels exactly.

V. Rates and Background

Production rates expected from each target are listed in Table 1. At modest beam intensities, hundreds of detected $K_{\pi 3}$/pulse result, and the flux of charged particles in the spectrometer is reasonable.

Besides the two charged particles and two gamma-rays demanded by the trigger, large area veto counters could be placed on the entrance face of the analyzing magnet to veto (high multiplicity) neutron interactions. Reconstructing the invariant mass of the four particles and demanding that it be close to the K^0, and demanding that the K^0 trajectory point to one of the two targets should reduce the neutron contamination to negligible levels. Λ^0's sneaking into the trigger could be reduced by placing a small veto counter in the place where protons from Λ^0 decay go, or by demanding more symmetric decays. Off-line Λ^0 and $K_{\pi 2}$ rejection should be complete.

VI. Plan for Data Collection

We propose to split the data collection into two phases. In phase 1 we would use the present spectrometer modified in two ways: drift chambers would be added, and the beam line would be modified so that the present beam could strike one of two targets that could be placed in the beam by remote control. This latter task requires moving one of the vertical bending magnets just upstream of the hyperon magnet, and adding the two target placement devices necessary. The rates of Table 1 are directly applicable to this case. If we collected 100 $K_{\pi 3}$/pulse, a week's running would yield about 3 M events, which we would split equally between the two targets. With this data sample we would achieve a statistical accuracy of .003. In performing this phase 1 test we would learn the following:

1) how to trigger most efficiently on $K_{\pi 3}$'s. Past experience in the M2 beam shows that collecting 100 events/pulse is possible, but no attempt has ever been made to increase the rate above that.

2) the best way to handle systematic errors. With 1/3% accuracy to shoot for, Monte Carlo calculations should be an excellent guide to understanding the data.

3) how best to do the second phase of the experiment, collecting 150 M events with controlable systematic errors.

The result of this phase 1 test would be some excellent physics: we would decrease the experimental error (or upper limit) on $|\eta_{+-0}|$ by two orders of magnitude, pushing it down to the level where we might see something. In other words, we would answer the question, is $|\eta_{+-0}|$ anomalously large.

Phase 2 of the experiment would build on all that we learned from phase 1. We would require a double beam setup, faster data-collection capability, and a 6250 bpi tape drive. Lengthening the decay region to 24 m to make better use of higher momentum $K_{\pi 3}$'s would also necessitate moving the analysis magnet, Avis.

Phase 1 would require several weeks of tests and 200 hours of data taking. Phase 2 would require 1000 hours of beam for data collection.

VII. Necessary Equipment

We would expect the laboratory to provide the beam line, including the two movable targets, the two magnets currently in place in M2, the fast electronics, and PDP 11 computer. The only new items for phase 1 are the target moving devices.

The experimenters will provide the scintillation counters, MWPC's, lead-glass counters and drift chambers. Here the only new equipment is the drift chambers.

We would expect to fill 100-200 magnetic tapes with data during phase 1, and to do the analysis on the Fermilab Cyber 175 computers. We would need about 100 hours of computer time to accomplish this.

VIII. Conclusion

We have proposed an experiment to detect the difference between K_l and K_S by measuring the CP violation parameter η_{+-0}. We would do this in two phases: in phase 1 we would make the minimal modifications to our existing apparatus (the hyperon spectrometer in the M2 beam line), and run for 200 hours. We will measure η_{+-0} with an error of about .003.

With the knowledge gained from phase 1, we will undertake phase 2, collecting enough data to decrease the phase 1 error by a factor of 6. Phase 2 requires a double beam geometry in M2, and higher data rate capability. We will achieve a precision of $\frac{1}{2} \times 10^{-3}$ in the measurement of η_{+-0} in 1000 hours of running.

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TABLE 1. PRODUCTION RATES

Target	Interference	Normalization
Collimator hole	$.4 \times .4\ cm^2$	$.4 \times .4\ cm^2$
Thickness	24 cm Tungsten	7 cm Tungsten
Location	z=0	z=-20 m
Beam intensity	1×10^{10} ppp	1×10^{11} ppp
Decay length	14 m	14 m
$K_{\pi 3}$	200/pulse	180/pulse
Λ^0	170 k	60 k
$K_{\pi 2}$	70 k	5 k
n	7.5 M	1.5 M
γ	10 M	2 M
n interactions	75 k	15 k
γ conversions	6 k	1 k
Total decays and interactions	500 k	
$K_{\pi 3}$/1000 hr run with 24 m decay length	82 M	74 M

FIGURE CAPTIONS

1. Dalitz Plot Acceptance
2. $\overline{K}/K$ Ratios

3a. Elevation View of Apparatus

3b. Plan View of Double Beam

4. Proper Time Distributions
5. Kaon Momentum Resolution
6. Kaon Mass Resolution

7a. Z Vertex Resolution

7b. Z-Dependence of Acceptance

8. Proper Time Resolution
9. Target Position Resolution

Figure 1: Acceptance over Dalitz Plot

	.68	.76	.74	.71	.76	.76	.75						
.71	.77	.77	.76	.75	.74	.75	.75	.75					
.78	.78	.75	.76	.77	.77	.77	.77	.76	.77				
.78	.81	.80	.76	.77	.78	.78	.75	.76	.75	.77			
.75	.78	.81	.76	.79	.78	.77	.76	.77	.78	.76	.76		
.80	.81	.78	.78	.79	.78	.76	.74	.76	.74	.75	.75	.75	
.79	.80	.76	.84	.81	.78	.77	.78	.77	.77	.75	.73	.74	.73
	.77	.80	.82	.75	.77	.79	.80	.78	.78	.77	.76	.75	.77
		.80	.80	.82	.78	.75	.78	.77	.78	.78	.74	.75	.76
			.79	.84	.79	.73	.80	.76	.80	.77	.76	.74	.77
				.73	.80	.79	.79	.81	.79	.79	.76	.78	.69
					.83	.80	.84	.79	.78	.80	.76	.77	.78
							.76	.80	.78	.77	.73	.76	.74
									.79	.77	.78	.73	.73

T_- (MeV): 56, 48, 40, 32, 24, 16, 8, 0 (vertical axis, top to bottom)

T_+ (MeV): 0, 8, 16, 24, 32, 40, 48, 56 (horizontal axis)

Figure 2: $\frac{\bar{K}}{K}$ Ratio

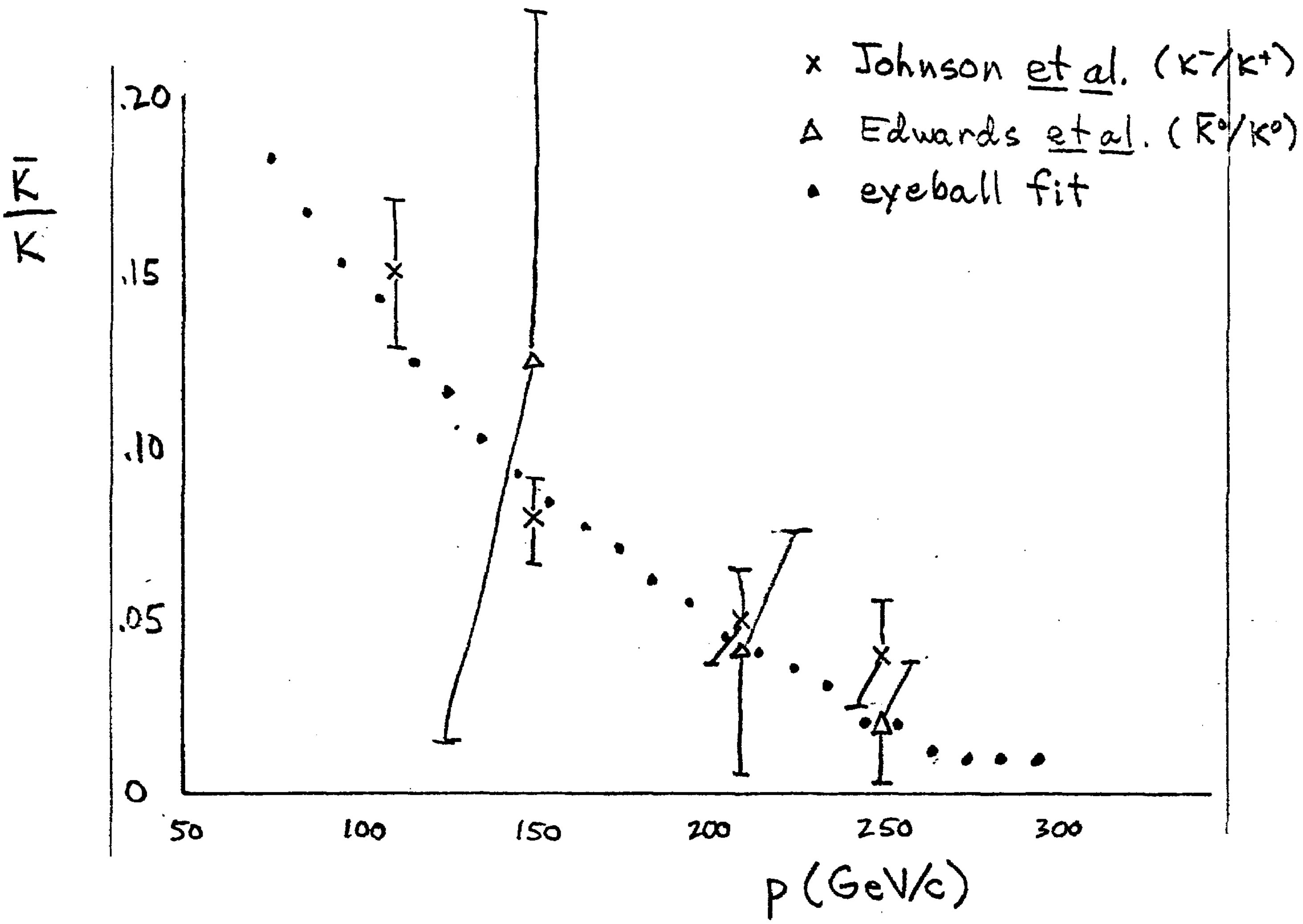


Figure 3a. Apparatus, Elevation View

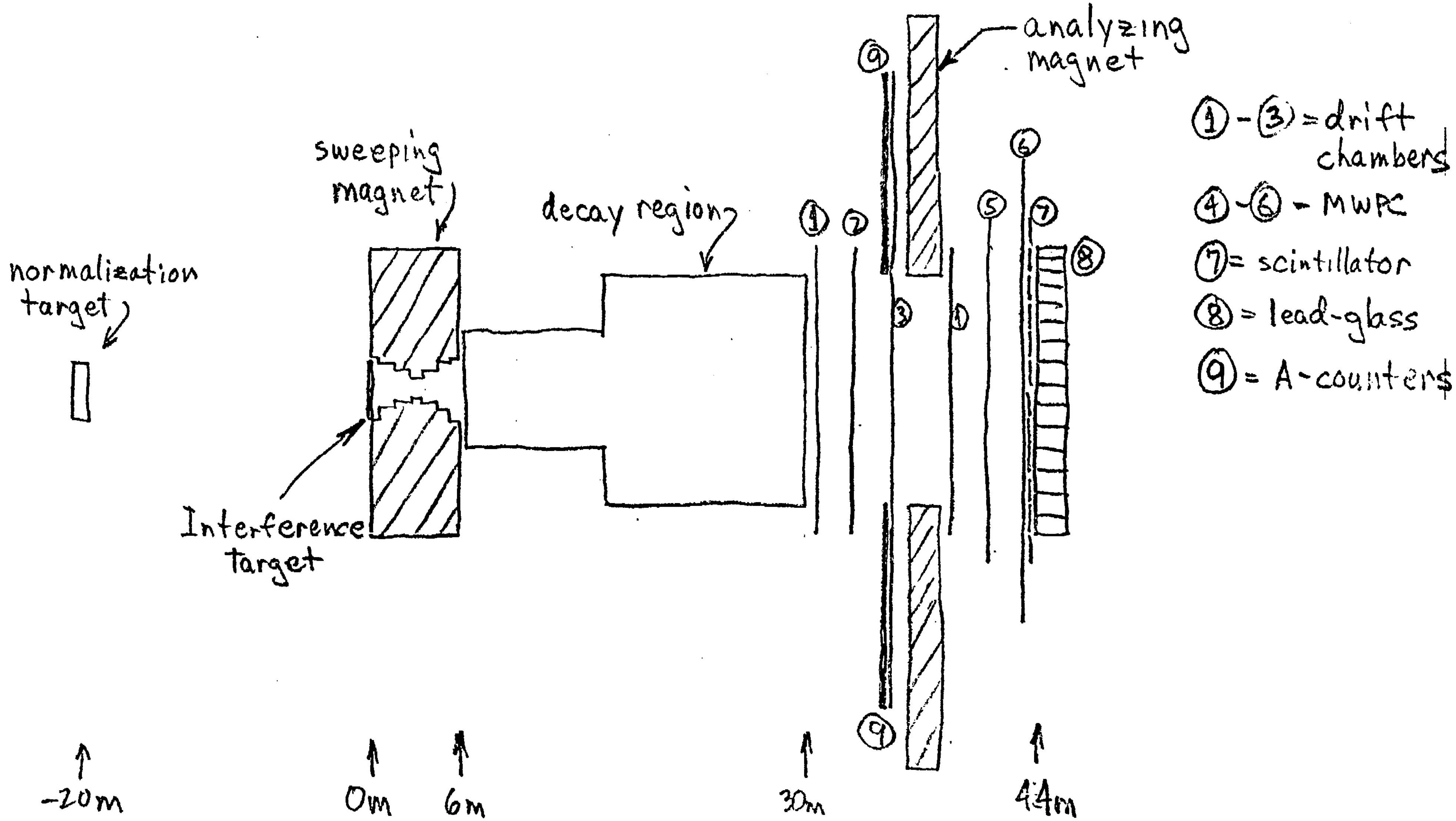
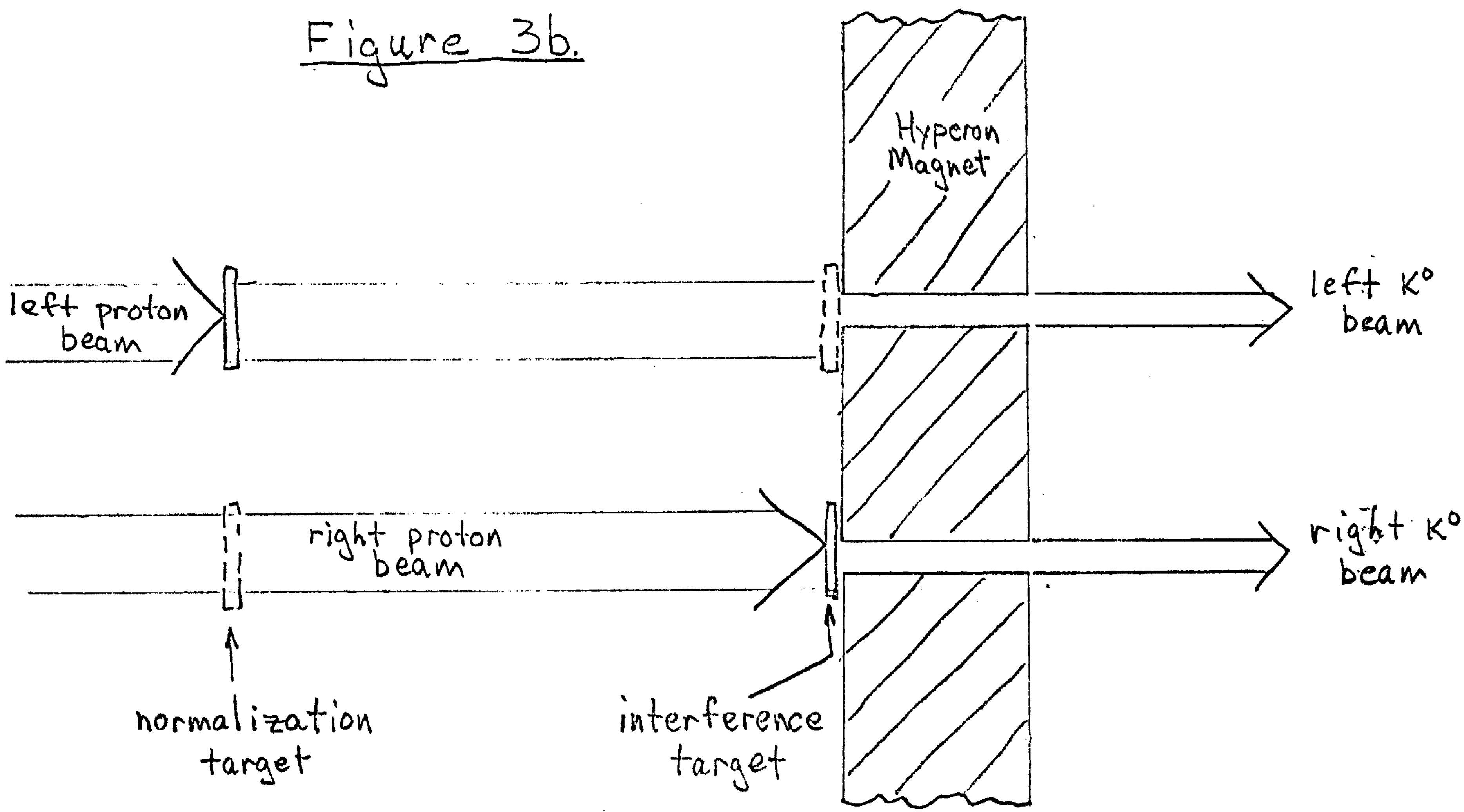


Figure 3b.



Hyperon Magnet
left proton beam
left K° beam
right proton beam
right K° beam
normalization target
interference target

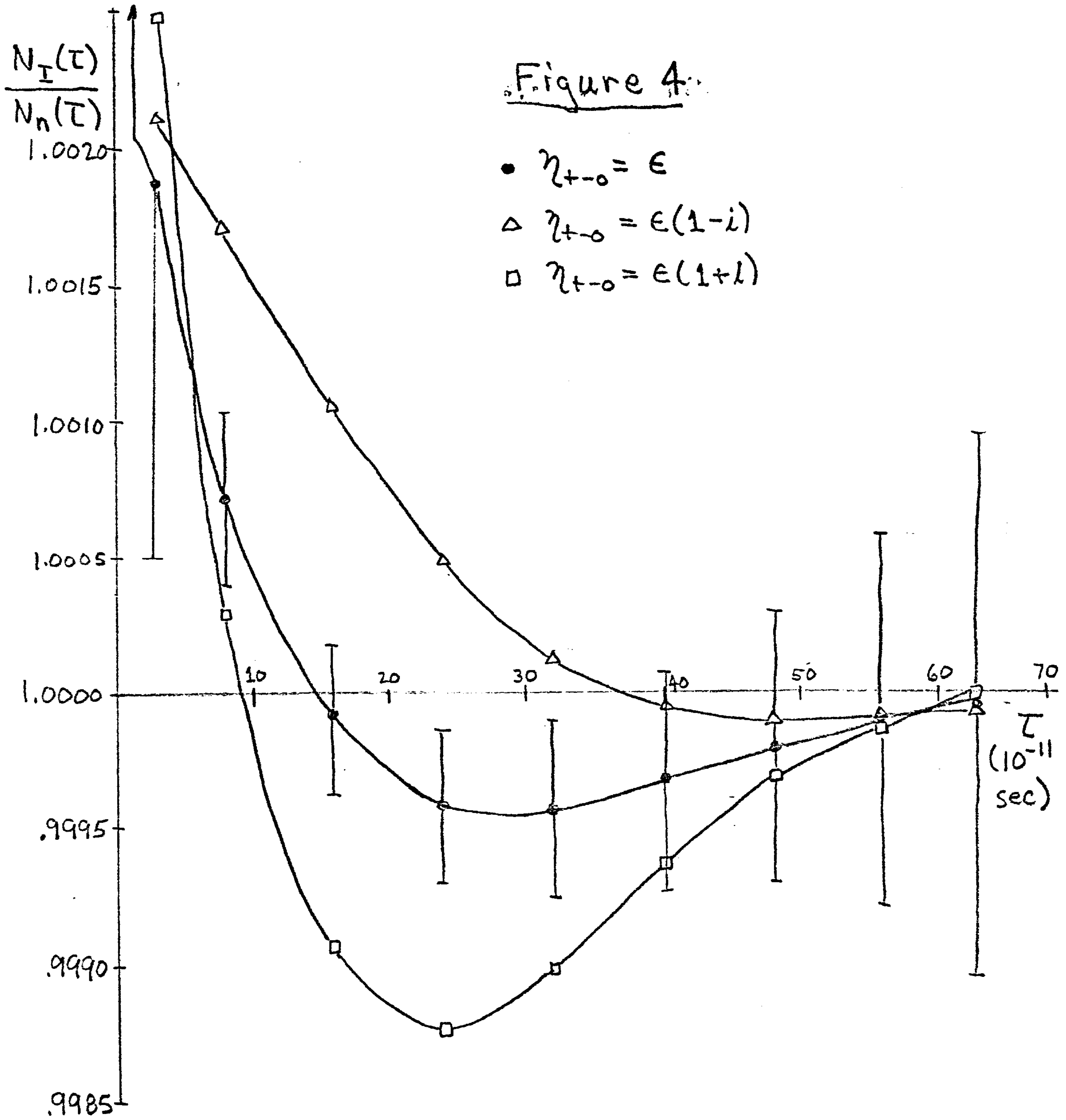


Figure 4
$\eta_{+-0} = \epsilon$
$\eta_{+-0} = \epsilon(1-i)$
$\eta_{+-0} = \epsilon(1+i)$
$\frac{N_I(\tau)}{N_n(\tau)}$
1.0020
1.0015
1.0010
1.0005
1.0000
.9995
.9990
.9985
10
20
30
40
50
60
70
τ (10^{-11} sec)

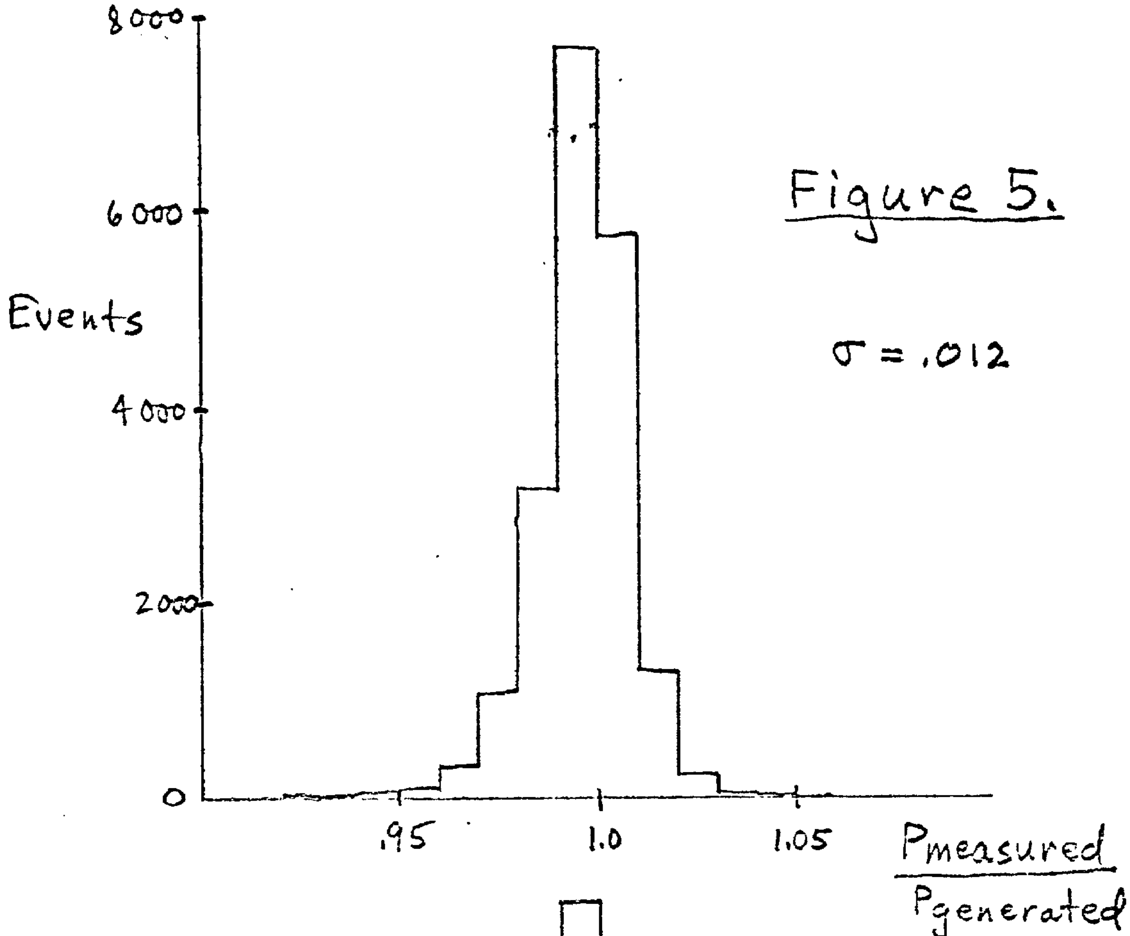


Figure 5.

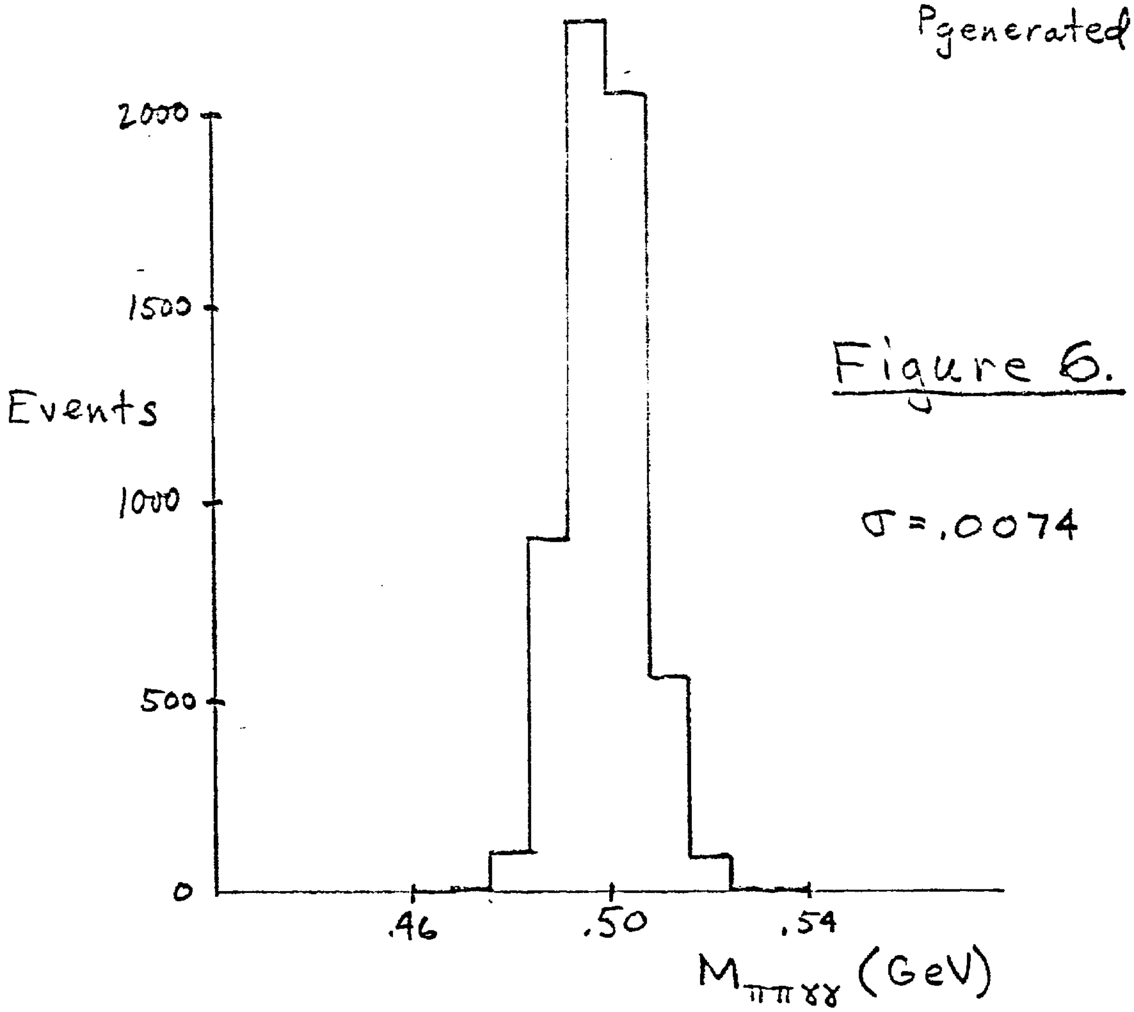
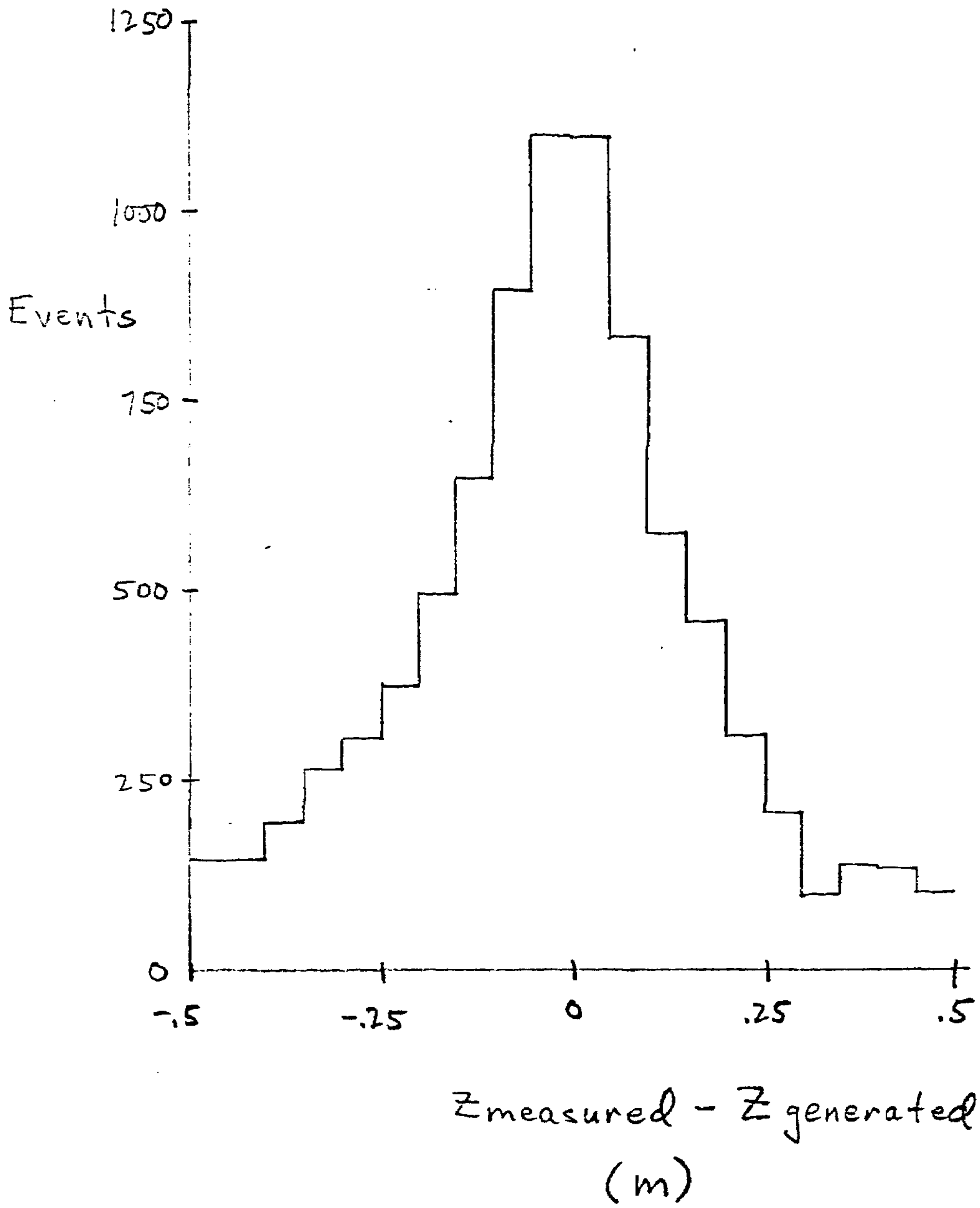


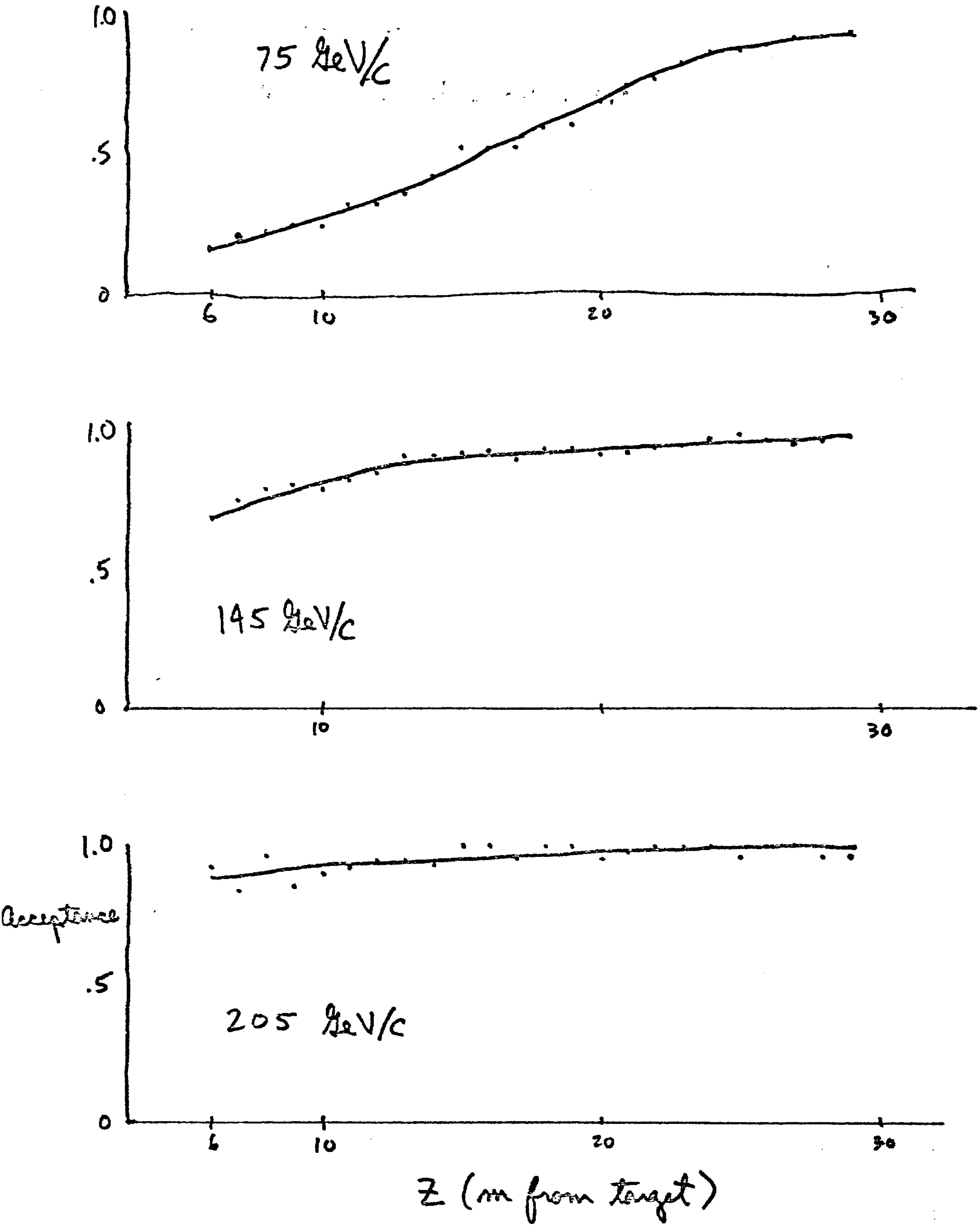
Figure 6.

Figure 7a.



1250
1000
Events
750
500
250
0
-.5
-.25
0
.25
.5
Zmeasured - Z generated
(m)

Figure 7b: Z-Dependence of Acceptance



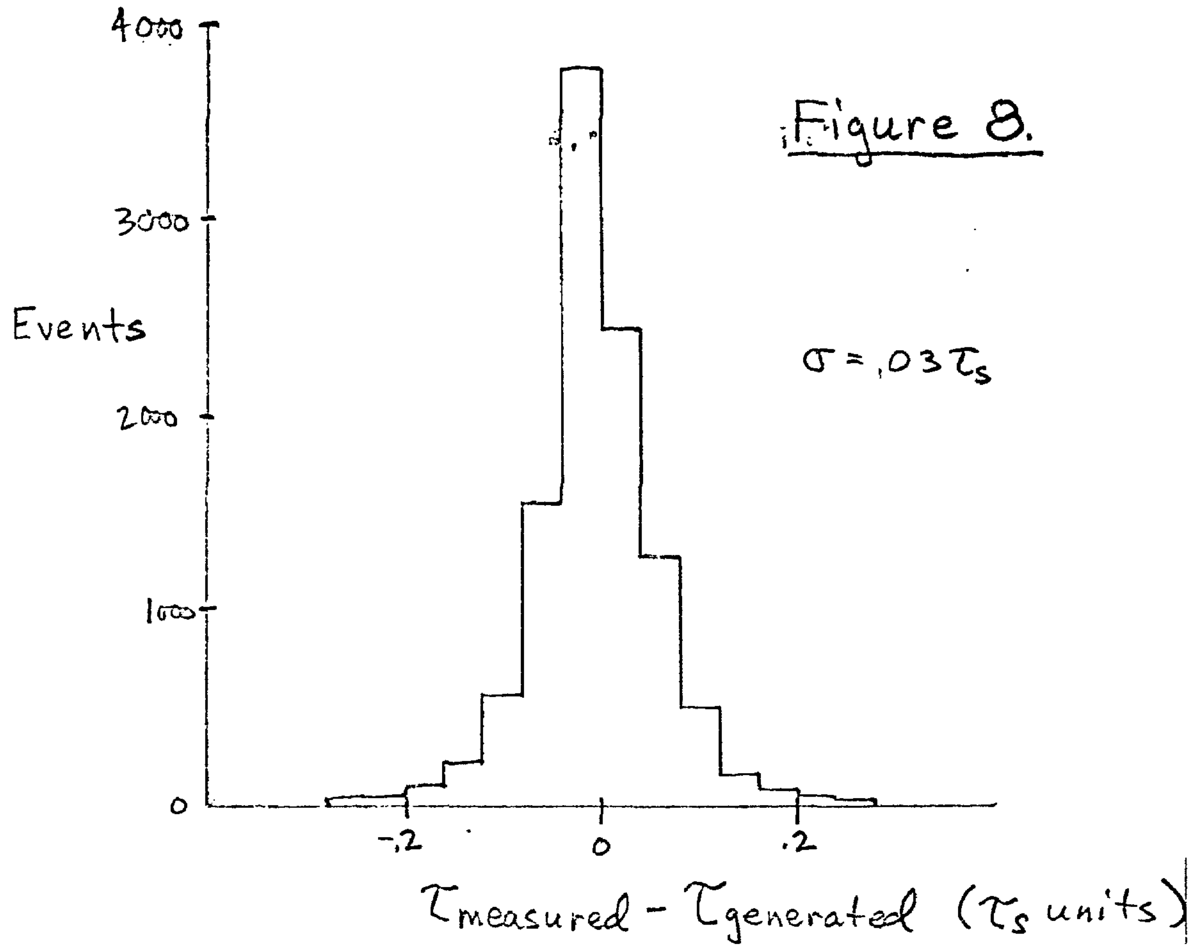


Figure 8.

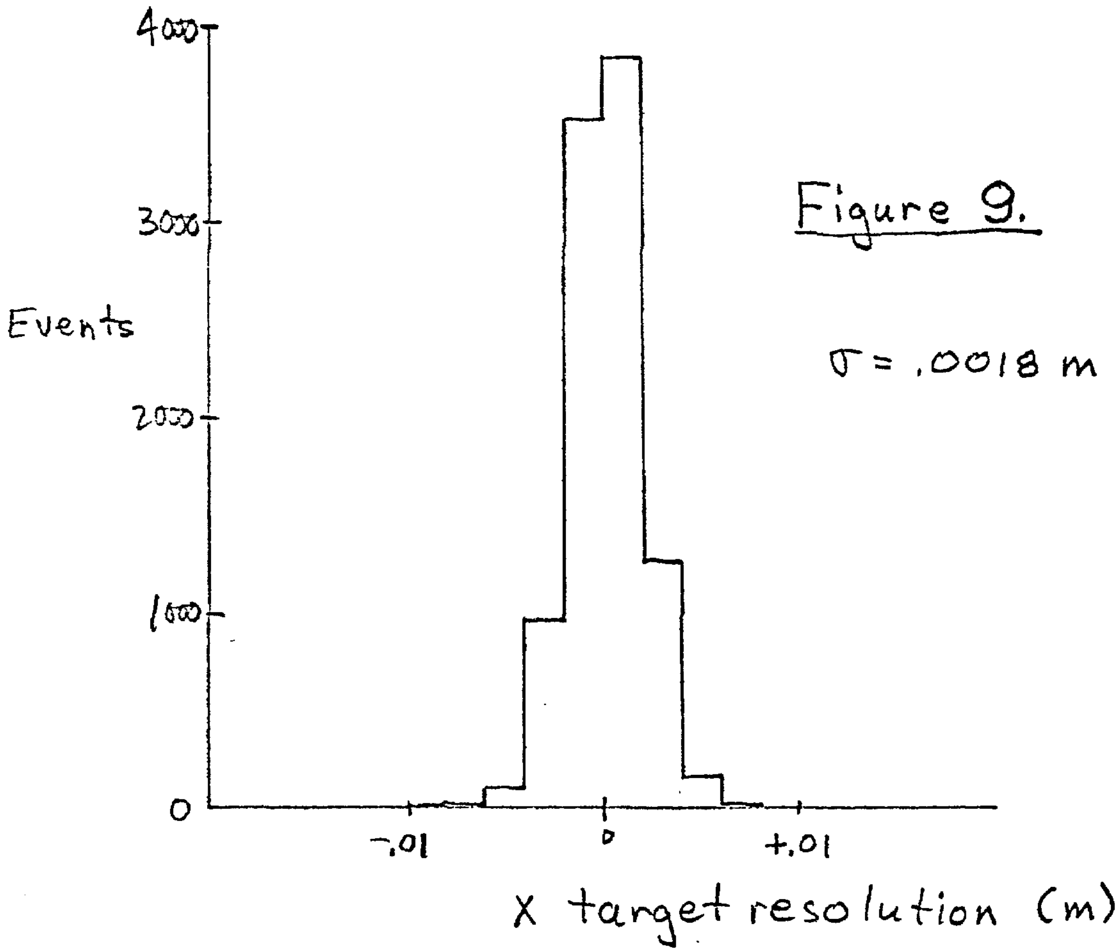


Figure 9.